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CORROSION RATES OF SELECTED ALLOYS IN THE DEEP OCEAN

by

J. B. Crilly and W. S. Haynes, Ph. D.

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U. S. NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California

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ABSTRACT

Corrosion rate data are given for several sets of metals and alloys exposed to the deep ocean environment off the coast of southern California at a depth of 5300 feet for 1064 days. The sets include some aluminum alloys; stainless steels; brasses and bronzes; titanium alloys; alloys containing nickel, chromium and other metals; a nickel-copper alloy; as well as sets of copper, lead and wrought iron. All specimens of six of these sets did not corrode at all. In some of the other sets there was relatively uniform corrosion up to rates of about 6 $mg/dm^2/day$, but in others the individual specimens varied considerably in their corrosion rates.

INTRODUCTION

The Naval Facilities Engineering Command has been directed to plan, design, construct and maintain the Naval Shore Establishment in support of the operating forces. As Navy activities and technology in the undersea environment expand, the new discipline of Deep Ocean Engineering broadens the scope of this directive.

In support of the Naval Facilities Engineering Command the Naval Civil Engineering Laboratory, Port Hueneme, California, has embarked on a vigorous program of research, development, testing and evaluation to encompass a wide range of deep ocean investigations. Among these are underwater construction, effects of the chemical and biological environment on materials, placing and recovering heavy loads, deep ocean anchorages, underwater nuclear power, trafficability on the ocean floor, core boring, underwater illumination and television, protective coatings.

The work reported in this paper is the result of 1064 days of exposure of selected alloys to the deep ocean environment at 5300 feet off the coast of southern California (33° 46' North, 123° 37' West) from 29 March 1962 to 25 February 1965. The following data were obtained as the result of sampling the water and ocean floor in the vicinity of this placement: salinity, 34.56 parts/thousand; oxygen concentration, 1.80 parts/million (1.26 ml/liter); temperature, 2.53 C (36.55 F); pH, 7.44; E_h (oxidation-reduction potential), +215 millivolts; pressure, 2350 psi; current, less than 0.5 knot; sediment, green firm mud and rocks.

PROCEDURES AND RESULTS

Samples 1 x 6 inches were sawn from large sheets and several were set aside for controls. Five samples of each metal were available in most cases; they were burnished by hand with a scrubber sold for cleaning pots and pans or an eraser depending upon hardness. They were solvent degreased put in polyethylene bags and stored in a desiccator until ready for use.

The samples were weighed and immediately replaced in the bags. They were then taken to a 20% humidity room and loaded onto test racks which were kept there until they could be attached to a submersible test unit (STU I-1), Figure 1. None of the samples were stressed; the nylon bolts holding them in place were barely finger-tightened.

After all test racks were loaded onto the STU, it was wrapped in polyethylene film which covered it until it was ready for lowering overboard from a ship for emplacement on the ocean floor. The list of metals exposed and reported here is given in Table 1. There were 6 copper alloys (3 bronzes and 3 brasses) and electrolytic copper; 6 aluminum alloys (1 clad); 3 titanium alloys; 4 stainless steels; 3 nickel-chromium alloys; a nickel-copper alloy; wrought iron; and lead. The densities of these metals, included in Table 1 as a matter of information, are used later to convert corrosion rates in milligrams per square decimeter per day (MDD) to rates expressed in mils per year (MPY).

The metals were analyzed at the San Francisco Bay Naval Shipyard (formerly Mare Island Naval Shipyard) and the results are given in Table 2. The samples of wrought iron were 6 inch lengths cut from pipe by quartering it lengthwise. These were added on short notice and samples were not submitted to analysis. Specification data where available are given.

Although only twenty-six different metals and alloys are reported, in two cases there were two sets of different heats, or lots, exposed--one was Al 3003 (Sample Nos. 68 and 71) and the other, Ni-Cu 400 (Nos. 73 and 74). When the specimens were first obtained it was believed that one set of each of these was a different alloy, but the analytical data received later established their actual nature. The specification requirements for two of the titanium alloys, Nos. 55 and 57, were unknown. These were identified later and are included in Table 2, but analytical data called for by the specification requirements, for hydrogen, nitrogen, oxygen and carbon, had not been obtained. Except for set No. 63, supposedly manganese bronze, in which analysis established the absence of manganese, and these two titanium alloys, all other test specimens for which specification requirements are available met those requirements, within the limits of metal uniformity and/or analytical data.

After recovery of the STU, Figure 2, on February 25, 1965, the sample racks were removed and photographed. The racks were disassembled and the corrosion products on the test specimens were removed by scraping and chemical cleaning. Figures 3 through 29 show test specimens before and after cleaning as well as close-up views where significant corrosion was evident. In a few cases where no visible changes in appearance or weight loss occurred, pictures were not taken after cleaning.

Corrosion rates, in milligrams per square decimenter of total metal per day, are given in Table 3. These corrosion rates converted to mils per year have been included in Table 3 to provide a better basis for comparison in cases where corrosion was relatively uniform but densities differ. Descriptive comments on nature of the corrosion are also given. Visual examination of the test specimens after cleaning revealed interesting information. Six sets of the metal specimens suffered no noticeable (nor measurable) effects from their exposure to sea water for almost three years at a depth of 5300 feet; these were stainless steel PH 15-7 MO, Cond. A;

stainless steel 321; Ti-4Al-3Mo-1V; Ti-140A; Ti-6Al-4V; and, Ni-Cr-Co-Mo 41.

Corrosive attack varied considerably within each of a few sets of specimens. In these cases the corrosion rate for each specimen exposed (rather than the average rate) is given in Table 3 to demonstrate the extent of this variability. In at least one specimen of each of the following sets there was practically no evidence of corrosion: stainless steel 17-7 PH, Cond. A; Ni-Cr-Fe-Ti X-750; Ni-Cr-Fe-Ti 600, Cond. A; and stainless steel 304. As would be expected in these cases, the corroded samples exhibited non-uniform corrosion. Two of the five samples of stainless steel 17-7 PH had very severe local pitting, enlarged below the surface, and crevice corrosion under the nylon bolt heads. Two of the Ni-Cr-Fe-Ti X-750 specimens corroded under the nut, burrowing underneath the metal surface; overall loss was not great but quite concentrated where it did occur. Only one of the five Ni-Cr-Fe-Ti 600 specimens showed isolated pits in the area about the nut. Of the four stainless steel 304 specimens, one showed severe local pitting and crevice corrosion under the nylon bolt head; another evidenced this to a lesser degree and the other two showed negligible corrosion. On the other hand, of the two sets of Ni-Cu 400 exposed, one annealed and the other from a different heat, all specimens exhibited high rates of corrosion and also considerable variation between specimens within each set. There was severe tuberculation around the nuts and crevice corrosion under them in all cases, and tubercules were evident along sawn edges as well as in isolated areas on the surfaces. Cleaning revealed nicks along the edges.

Of the sixteen remaining sets of metals, the corrosion rates and appearance of all specimens of a set were in good agreement--corrosion rates for all members of thirteen of these sets falling within ten percent of the arithmetic mean. All test specimens of three of these metals corroded at a rate less than 1.0 MDD: aluminum 5052-H22, aluminum bronze, and lead. Aluminum Alclad 7075-0 and phosphor bronze corroded at rates of 2.0 MDD and just above. In the aluminum Alclad there was no pitting or other localized corrosion, but the corrosion of the aluminum 5052-H22, to the extent occurring, was concentrated mostly under the nylon bolt heads with a little damage on the cut edges. The aluminum bronze showed very slight corrosion in tiny spots. A thin film of corrosion products formed on the phosphor bronze specimens, and some scale. The lead samples had a thin blue adherent film with no damage underneath. Seven of the remaining sets corroded at rates between 3.0 and 4.0 MDD, and samples of commercial brass at rates from 4.0 to 5.6. In the latter case the only visible evidence of corrosion was a slight surface staining. The seven sets, together with descriptions, were: wrought iron, with uniform corrosion (no pitting); electrolytic copper, small tubercules and some streaking corrosion products with slight scaling; yellow brass, with slight surface staining only; both sets of the aluminum 3003 showing severe crevice corrosion from the cut edges; aluminum 1100-0 samples severely pitting and with crevice corrosion

around the nylon bolt heads; and, aluminum 2024-T3, with some surface pitting, some corrosion under the nylon bolt heads, and severe crevice corrosion resulting in a layered structure. Samples of the last three sets corroded at rates between 5.0 and 6.0 MDD: aluminum 7178-0, with severe pitting spreading to sizeable areas in some cases to perforation; bronze, with many small tubercules, and larger ones evident about some of the nylon bolt heads; and, naval brass, which did not appear seriously corroded in spite of the high corrosion rates, suggesting dezincification.

The corrosion rates of twelve of these same metals exposed to a near-surface ocean environment in the Port Hueneme, California harbor were determined several years ago.[1] These are shown in Table 4. For those metals exposed to both that environment and the deep ocean environment off the coast of California, there were significantly higher corrosion rates near the surface for the samples of lead, aluminum bronze and phosphor bronze. On the other hand, the corrosion rates were higher in the ocean depths for aluminum 3003, aluminum 1100-0, and aluminum 2024-T3.

Estimated costs as finished sheet of the different alloys exposed are given in Table 4 so that economic factors can be taken into account in selecting an alloy for use in the ocean depths. These factors can not receive overriding weight, but can be considered for those metals that meet other firm usage requirements. Factors given a high priority in selecting a metal for a particular piece of equipment in any deep ocean environment would include structural requirements, thermal or electrical conductance, and avoidance of sacrificial metallic couplings (unless intentional to protect the more noble metal). A salesman for a distributor of titanium alloys stated that commercially pure titanium will do as well or better in a marine environment than the titanium alloys included in this program and quoted a price of $7.30 per lb. as compared to $12.10 or $13.00 for two of the alloys. No test specimen of this material was included so no data was available from these experiments to verify this statement.

CONCLUSIONS

From a consideration of both corrosion rates and economic factors given in Table 4, certain metals can be recommended for several years' use in an ocean environment near the ocean floor comparable to that off the coast of southern California where the alloys included in this report were exposed. Other factors dependent on the required functioning of the metal would receive equal or even greater emphasis. The metals recommended on the basis of these findings are the two stainless steels, PH 15-7 MO, Cond. A, and 321. However, it must be remembered that stainless steels are notorious for a lack of uniform behavior in an ocean environment. They should not be depended on to meet a critical requirement in the ocean depths. The titanium alloys and Ni-Cr-Co-41 exposed performed equally

well for the same period but are all considerably more expensive. The Ni-Cr-Co-41 alloy is economically most favored of the four. If a little greater susceptibility to corrosion is acceptable to reduce material costs by about ten percent, three other metals can be suggested, within the limits of their suitability for intended requirements: aluminum 5052-H22, aluminum bronze, or lead.

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REFERENCE

1. Carl V. Brouillette, "Corrosion Rates in Port Hueneme Harbor," Corrosion, 14, 352t (1958).

Table 1. Alloys Exposed

Sample No.	Alloy	Specification	Density, g/cm^3
48	Aluminum Alclad 7075-0	QQ-A-287	2.80
49	Aluminum 7178-0	MIL-A-9180	2.81
68	Aluminum 3003-H24	QQ-A-359	2.73
69	Aluminum 1100-0	QQ-A-561	2.71
70	Aluminum 5052-H22	QQ-A-318	2.68
71	Aluminum 3003 (different heat from No. 68)	QQ-A-359	2.73
72	Aluminum 2024-T3	QQ-A-362	2.77
59	Phosphor Bronze	QQ-P-330, Comp. A	8.86
60	Naval Brass	MIL-N-994, Comp. A	8.41
62	Aluminum Bronze	QQ-B-667, Comp. 3	7.89
63	Manganese Bronze*	QQ-M-80, Class A	8.36
65	Commercial Brass	63-68 Cu, Comp. A	8.47
66	Copper, Electrolytic	QQ-C-576	8.92
67	Yellow Brass	Revere Alloy 170	8.47
73	Ni-Cu 400, Annealed	QQ-N-281, Class A	8.84
74	Ni-Cu 400 (different heat from No. 73)	QQ-N-281	8.84
53	Ni-Cr-Fe-Ti X-750	AMS-5542-D	8.25
54	Ni-Cr-Fe-Ti 600, Cond. A	MIL-N-6840	8.43
58	Ni-Cr-Co-Mo 41	Unknown	8.25
50	Stainless Steel PH 15-7 MO, Cond. A	AISI, Type 632	7.80
51	Stainless Steel 17-7 PH, Cond. A	MIL-S-25043B	7.81
52	Stainless Steel 321	MIL-S-6721A	7.92
64	Stainless Steel 304	MIL-S-854, Class 1	7.92
132	Wrought Iron	Unknown	7.70
55	Ti-4Al-3Mo-1V**	AMS 4912	4.52
56	Ti-140A (not a standard alloy)	NA2-7125J, Class B	4.74
57	Ti-6Al-4V**	AMS-4928A	4.43
61	Lead	QQ-L-201, Grade B	11.34

* Specification analysis established absence of manganese.
** Does not conform.

Table 2. Analyses of Metals

Aluminum Alclad 7075-0; QQ-A-287 (No. 48)

	Core		Clad	
	Requirements, %	Results, %	Requirements, %	Results, %
Aluminum	(rem*)	rem*	(rem*)	rem*
Zinc	(5.1 - 6.1)	5.65	(0.8 - 1.3)	1.34
Magnesium	(2.1 - 2.9)	2.45	(0.10 max)	0.10
Copper	(1.2 - 2.0)	1.53	(0.10 max)	0.05
Chromium	(0.18 - 0.40)	0.22	----------	0.03
Manganese	(0.3 max)	0.06	(0.10 max)	<0.01
Iron	(0.7 max)	0.25		
Silicon	(0.5 max)	0.17		
Iron + Silicon			(0.7 max)	0.39
Titanium	(0.2 max)	0.03		
Other Elements	(0.05 max)	<0.05	----------	<0.05
Total Other Elements	(0.15 max)	<0.15	----------	<0.15

Conforms

Aluminum 7178-0; MIL-A-9180 (No. 49)

	Requirements, %	Test Results, %
Aluminum	(rem*)	rem*
Zinc	(6.3 - 7.3)	6.31
Magnesium	(2.4 - 3.1)	2.50
Copper	(1.6 - 2.4)	1.73
Chromium	(0.18 - 0.40)	0.19
Manganese	(0.3 max)	0.05
Iron	(0.7 max)	0.15
Silicon	(0.5 max)	0.19
Titanium	(0.2 max)	0.04
Other Elements	(0.05 max)	<0.05
Total Other Elements	(0.15 max)	<0.15

Conforms

* remainder

Table 2. (Cont'd)

Stainless Steel PH 15-7 MO, Cond. A; AISI, Type 632 (No. 50)

	Requirements, %	Test Results, %
Carbon	(0.09 max)	0.10
Manganese	(1.10 max)	0.52
Phosphorus	(0.040 max)	0.023
Sulfur	(0.040 max)	0.008
Silicon	(1.00 max)	0.33
Chromium	(14.00 - 16.00)	15.37
Nickel	(6.50 - 7.75)	7.07
Molybdenum	(2.00 - 3.00)	2.19
Aluminum	(0.75 - 1.50)	1.05

Conforms, except carbon is borderline

Stainless Steel 17-7 PH, Cond. A; MIL-S-25043B (No. 51)

	Requirements, %	Test Results, %
Carbon	(0.09 max)	0.09
Manganese	(1.0 max)	0.48
Phosphorus	(0.04 max)	0.021
Sulfur	(0.03 max)	0.006
Silicon	(1.0 max)	0.33
Chromium	(16 - 18)	16.76
Nickel	(6.5 - 7.75)	6.98
Aluminum	(0.75 - 1.5)	1.32

Conforms

Stainless Steel 321; MIL-S-6721A (No. 52)

	Requirements, %	Test Results, %
Carbon	(0.08 max)	0.08
Manganese	(2.0 max)	1.52
Phosphorus	(0.04 max)	0.028
Sulfur	(0.03 max)	0.010
Silicon	(1.0 max)	0.91
Chromium	(17 - 19)	17.32
Nickel	(8 - 11)	10.21
Copper	(0.5 max)	0.35
Titanium	(0.75 max)	0.55

Conforms

Table 2. (Cont'd)

Ni-Cr-Fe-Ti X-750; AMS-5542-D (No. 53)

	Requirements, %	Test Results, %
Copper	(0.5 max)	0.09
Nickel + Cobalt	(70 min)	73.41
Iron	(5.0 - 9.0)	6.90
Manganese	(1.0 max)	0.55
Chromium	(14 - 17)	14.50
Silicon	(0.5 max)	0.36
Carbon	(0.08 max)	0.08
Sulfur	(0.01 max)	0.003
Titanium	(2.25 - 2.75)	2.40
Aluminum	(0.4 - 1.0)	0.81
Columbium + Tantalum	(0.7 - 1.2)	0.90

Conforms

Ni-Cr-Fe-Ti 600, Cond. A; MIL-N-6840 (No. 54)

	Requirements, %	Test Results, %
Copper	(0.5 max)	0.38
Nickel + Cobalt	(72 min)	75.26
Iron	(6.0 - 10.0)	7.25
Manganese	(1.0 max)	0.18
Chromium	(14 - 17)	16.00
Silicon	(0.5 max)	0.27
Carbon	(0.15 max)	0.06
Sulfur	(0.015 max)	0.008

Conforms

Ti-4Al-3Mo-1V; AMS 4912 (No. 55)

	Requirements, %	Test Results, %
Titanium	--------	rem*
Manganese	--------	<0.1
Aluminum	(3.75 - 4.75)	4.5
Iron	(0.25 max)	0.1
Chromium	--------	0.2
Molybdenum	(2.5 - 3.5)	3.7
Vanadium	(0.5 - 1.5)	0.9
Silicon	--------	<0.05
Hydrogen	(0.015 max)	not determined
Nitrogen	(0.05 max)	" "
Carbon	(0.08 max)	" "

Molybdenum slightly high

* remainder

Table 2. (Cont'd)

Ti-140A; not a standard alloy; NA2-7125J, Class B (No. 56)

	Requirements, %	Test Results %
Titanium	unknown	rem*
Manganese	"	<0.01
Aluminum	"	<0.1
Iron	"	1.9
Chromium	"	2.1
Molybdenum	"	1.9
Vanadium	"	<0.1
Silicon	"	<0.1

Ti-6Al-4V; AMS-4928A (No. 57)

	Requirements, %	Test Results, %
Titanium	---------	rem*
Manganese	---------	<0.1
Aluminum	(5.5 - 6.5)	7.2
Iron	(0.25 max)	<0.1
Chromium	---------	<0.1
Molybdenum	---------	<0.1
Vanadium	(3.5 - 4.5)	5.2
Silicon	(0.08 max)	<0.1
Nitrogen	(0.05 max)	not determined
Hydrogen	(0.015 max)	" "
Oxygen	(0.20 max)	" "

Aluminum and Vanadium high

Ni-Cr-Co-Mo 41; unknown (No. 58)

	Requirements %	Test Results %
Carbon	---------	0.11
Chromium	---------	19.08
Nickel	---------	55.29
Tungsten	---------	nil
Iron	---------	0.33
Cobalt	---------	11.47
Molybdenum	---------	9.72
Manganese	---------	<0.01
Silicon	---------	0.07
Titanium	---------	3.34

* remainder

Table 2. (Cont'd)

Phosphor Bronze; QQ-P-330, Comp. A (No. 59)

	Requirements, %	Test Results, %
Copper	(rem*)	95.29
Tin	(3.5 - 5.8)	4.44
Zinc	(0.3 max)	<0.10
Lead	(0.05 max)	<0.05
Phosphorus	(0.03 - 0.35)	0.06
Iron	(0.1 max)	<0.05
Copper + Tin + Phosphorus	(99.5 min)	99.66

Conforms

Naval Brass; MIL-N-994, Comp. A (No. 60)

	Requirements, %	Test Results, %
Copper	(59 - 63)	60.46
Tin	(0.5 - 1.0)	0.69
Zinc	(rem*)	38.74
Lead	(0.2 max)	0.08
Iron	(0.1 max)	0.03
Total Other Elements	(0.1 max)	<0.10

Conforms

Lead; QQ-L-201, Grade B (No. 61)

	Requirements, %	Test Results, %
Lead	(99.50 min)	99.91

Conforms

* remainder

Table 2. (Cont'd)

Aluminum Bronze; QQ-B-667, Comp. 3 (No. 62)

	Requirements, %	Test Results, %
Copper	(92 - 96)	95.11
Iron	(0.5 max)	<0.05
Aluminum	(4.0 - 7.0)	4.76
Others	(0.50 max)	<0.50

Conforms

Manganese Bronze; QQ-M-80, Class A (No. 63)

	Requirements, %	Test Results, %
Copper	(57 - 60)	58.94
Zinc	(rem*)	39.07
Tin	(0.5 - 1.5)	0.89
Iron	(0.8 - 2.0)	1.10
Lead	(0.2 max)	<0.05
Manganese	(0.05 - 0.5)	nil
Aluminum	(0.25 max)	<0.10
Total Other Elements	(0.1 max)	<0.10

Manganese absent

Stainless Steel 304; MIL-S-854, Class 1 (No. 64)

	Requirements, %	Test Results %
Carbon	(0.08 max)	0.05
Manganese	(2.0 max)	1.46
Phosphorus	(0.04 max)	0.034
Sulfur	(0.04 max)	0.008
Silicon	(1.0 max)	0.43
Chromium	(18 min)	18.00
Nickel	(8 min)	9.08
Copper	(0.5 max)	<0.05

Conforms

*remainder

Table 2. (Cont'd)

Commercial Brass; 63-68 Cu, Comp. A (No. 65)

	Requirements, %	Test Results, %
Copper	(63 - 68)	66.47
Tin		<0.05
Zinc		33.51
Lead		<0.01
Iron		0.02
Total Other Elements		<0.10

Conforms

Copper, Electrolytic; QQ-C-576 (No. 66)

	Requirements, %	Test Results, %
Copper	(99.88)	99.97

Conforms

Yellow Brass; Revere Alloy 170 (No. 67)

	Requirements, %	Test Results, %
Copper	(65 nominal)	68.48
Tin		<0.05
Zinc	(35 nominal)	31.50
Lead		<0.01
Iron		0.02
Total Other Elements		0.10

Conforms

Table 2. (Cont'd)

Aluminum 3003-H24; QQ-A-359 (No. 68)

	Requirements, %	Test Results, %
Aluminum	(rem*)	rem*
Zinc	(0.1 max)	0.08
Copper	(0.2 max)	0.16
Manganese	(1.0 - 1.5)	1.10
Iron	(0.7 max)	0.48
Silicon	(0.6 max)	0.10
Other Elements (each)	(0.05 max)	<0.05
Total Other Elements	(0.15 max)	<0.15

Conforms

Aluminum 1100-0; QQ-A-561 (No. 69)

	Requirements, %	Test Results, %
Aluminum	(99 min)	99.20
Zinc	(0.1 max)	0.06
Copper	(0.2 max)	0.14
Manganese	(0.05 max)	0.03
Iron + Silicon	(1.0 max)	0.57
Other Elements	(0.05 max)	<0.05
Total Other Elements	(0.15 max)	<0.15

Conforms

Aluminum 5052-H22; QQ-A-318 (No. 70)

	Requirements, %	Test Results, %
Aluminum	(rem*)	rem*
Zinc	(0.1 max)	0.07
Magnesium	(2.2 - 2.8)	2.50
Copper	(0.1 max)	0.05
Chromium	(0.15 - 0.35)	0.23
Manganese	(0.1 max)	<0.01
Iron + Silicon	(0.45 max)	0.23
Other Elements	(0.05 max)	<0.05
Total Other Elements	(0.15 max)	<0.15

Conforms

* remainder

Table 2. (Cont'd)

Aluminum 3003 (different heat from No. 68); QQ-A-359 (No. 71)

	Requirements, %	Test Results, %
Aluminum	(rem*)	rem*
Zinc	(0.1 max)	0.05
Copper	(0.2 max)	0.15
Manganese	(1.0 - 1.5)	1.25
Iron	(0.7 max)	0.45
Silicon	(0.6 max)	0.15
Other Elements (each)	(0.05 max)	---
Total Other Elements	(0.15 max)	---

Aluminum, 2024-T3; QQ-A-362 (No. 72)

	Requirements, %	Test Results, %
Aluminum	(rem*)	rem*
Zinc	(0.25 max)	0.15
Magnesium	(1.2 - 1.8)	1.50
Copper	(3.8 - 4.9)	4.20
Chromium	(0.1 max)	0.03
Manganese	(0.3 - 0.9)	0.68
Iron	(0.5 max)	0.22
Silicon	(0.5 max)	0.13
Other Elements	(0.05 max)	<0.05
Total Other Elements	(0.15 max)	<0.15

Conforms

Ni-Cu 400, Annealed; QQ-N-281, Class A (No. 73)

	Requirements, %	Test Results, %
Copper	(rem*)	29.25
Nickel	(63 - 70)	68.02
Iron	(2.5 max)	1.52
Manganese	(1.25 max)	0.99
Aluminum	(0.5 max)	<0.10
Silicon	(0.5 max)	<0.05
Carbon	(0.3 max)	0.12
Sulfur	(0.024 max)	0.010

Conforms

* remainder

Table 2. (Cont'd)

Ni-Cu 400 (different heat from No. 73); QQ-N-281 (No. 74)

	Requirements, %	Test Results, %
Nickel	(63 - 70)	65.90
Copper	(rem*)	31.75
Iron	(2.5 max)	1.07
Manganese	(1.25 max)	0.94
Silicon	(0.5 max)	0.19
Aluminum	(0.5 max)	<0.10
Carbon	(0.3 max)	0.14
Sulfur	(0.024 max)	0.01

Conforms

* remainder

Table 3. Corrosion Rates

Alloy	Sample No.	Corrosion Loss, MDD*	Corrosion Rate, MPY**
Aluminum Alclad 7075-0	S-48	2.1	1.1
The corrosion was not localized; no pits formed. Figure 3.			
Aluminum 7178-0	S-49	5.3	2.7
Severe pitting to perforation, particularly bad around the nylon bolt heads; corrosion loss varied less than 10% from mean for the five specimens. Each had more than 10 pits of depth greater than 60 mils, many of them of relatively large cross-section. Figure 4.			
Stainless Steel PH 15-7 MO, Cond. A	S-50	0.00	0.00
No surface change apparent. Figure 21.			
Stainless Steel 17-7 PH, Cond. A	S-51-1	3.3	0.61
	S-51-2	0.91	0.17
	S-51-3	3.6	0.66
	S-51-4	0.18	0.03
	S-51-5	0.00	0.00
Very severe local pitting, enlarged below the surface and a few penetrating completely; crevice corrosion under the nylon bolt head. On specimens 51-1, -2, and -3 the maximum pits were 61, 52, and 60 mils deep; average of ten deepest pits was 54, 32, 53 mils, respectively. Figure 22.			
Stainless Steel 321	S-52	0.00	0.00
No surface change. Figure 23.			

* milligrams/square decimeter/day
** mils/year

Table 3. (Cont'd)

Alloy	Sample No.	Corrosion Loss, MDD*	Corrosion Rate, MPY**
Ni-Cr-Fe-Ti X-750	S-53-1	0.01	0.00
	S-53-2	1.2	0.21
	S-53-3	0.01	0.00
	S-53-4	0.06	0.01
	S-53-5	2.1	0.37
Two of the specimens corroded under the nut, burrowing underneath the metal surface; overall loss not great but effect is quite concentrated where it does occur. Other three specimens show negligible corrosion. On specimens 53-2 and 53-5, deepest pit was 36 and 47 mils; average of ten deepest pits was 22 mils, 37 mils. Figure 18.			
Ni-Cr-Fe-Ti 600, Cond. A	S-54-1	0.01	0.00
	S-54-2	0.01	0.00
	S-54-3	0.01	0.00
	S-54-4	3.1	0.53
	S-54-5	0.01	0.00
In the one specimen there were isolated pits about the nuts; the other four showed very little sign of deterioration. On 54-4 the deepest pit was 51 mils and average of the ten deepest was 39 mils. Figure 19.			
Ti-4Al-3Mo-1V	S-55	0.00	0.00
No surface change apparent. Figure 26.			
Ti-140A (not a standard alloy)	S-56	0.00	0.00
No surface change apparent. Figure 27.			
Ti-6Al-4V	S-57	0.00	0.00
No surface change apparent. Figure 28.			

* milligrams/square decimeter/day
** mils/year

Table 3. (Cont'd)

Alloy	Sample No.	Corrosion Loss, MDD*	Corrosion Rate MPY**
Ni-Cr-Mo-41	S-58	0.00	0.00
No surface change apparent (only three specimens exposed). Figure 20.			
Phosphor Bronze	3-59	2.2	0.36
Thin film of corrosion products formed and then scale. Figure 9.			
Naval Brass	S-60	5.8	1.0
Although these specimens suffered next to the greatest corrosion loss in mdd, corrosion was so uniform that it was not evident from an examination of the test specimens. Figure 10.			
Lead	S-61	0.63	0.08
Thin, blue adherent film was found; no damage below film. Figure 29.			
Aluminum Bronze	S-62	0.81	0.15
Very slight corrosion occurred in tiny spots. Figure 11.			
Bronze	S-63	5.2	0.90
Many small tubercules with traces of flakiness; larger tubercules evident about some of the nylon bolt heads. Figure 12.			
Stainless Steel 304	S-64-1	3.2	0.58
	S-64-2	0.91	0.17
	S-64-3	0.00	0.00
	S-64-4	0.09	0.02
Severe local pitting and crevice corrosion under the nylon bolt head. On specimens 64-1 and 64-2 the deepest pit was 53 and 28 mils; average of ten deepest pits on 64-1 was 34 mils, but there were only six pits on 64-2, average depth of 9 mils. Figure 24.			

* milligrams/square decimeter/day
** mils/year

Table 3. (Cont'd)

Alloy	Sample No.	Corrosion Loss, MDD*	Corrosion Rate, MPY**
Commercial Brass	S-65	4.4	0.75
Slight surface staining. Figure 13.			
Copper, Electrolytic	S-66	3.1	0.50
Small tubercules and isolated streaking corrosion products, with slight scaling. Figure 14.			
Yellow Brass	S-67	3.7	0.63
Similar to S-65. Figure 15.			
Aluminum 3003-H24	S-68	3.5	1.8
Severe crevice corrosion under the bolt heads and from the cut edge. Figure 5.			
Aluminum 1100-0	S-69	3.4	1.8
Severe pitting and crevice corrosion around the nylon bolt heads. Figure 6.			
Aluminum 5052-H22	S-70	0.78	0.42
Corrosion concentrated mostly under the nylon bolt heads, with some damage on the cut edges. Figure 7.			
Aluminum 3003 (different heat from No. 68)	S-71	3.5	1.8
Performance like S-68. Figure 5.			

* milligrams/square decimeter/day
** mils/year

Table 3. (Cont'd)

Alloy	Sample No.	Corrosion Loss, MDD*	Corrosion Rate, MPY**
Aluminum 2024-T3	S-72	3.6	1.9
Some corrosion under the nylon bolt heads; some surface pitting. Very severe crevice corrosion to give a layered structure. Figure 8.			
Ni-Cu 400, Annealed	S-73-1	5.0	0.81
	S-73-2	4.8	0.78
	S-73-3	5.8	0.94
	S-73-4	5.0	0.81
	S-73-5	3.2	0.52
Tubercules evident along sawn edges which were removed upon cleaning to reveal nicks along the edges. Severe tuberculation around nuts in all cases. Figure 16.			
Ni-Cu 400 (different heat from No. 73)	S-74-1	6.5	1.1
	S-74-2	5.1	0.83
	S-74-3	8.1	1.3
	S-74-4	7.5	1.2
	S-74-5	7.3	1.2
Severe tuberculation and crevice corrosion under all nuts. Some but not all edges showed corrosion damage, although all the ends did; tubercules present in isolated areas on the surface. Figure 17.			
Wrought Iron	S-132	3.1	0.58
Even corrosion with no pitting. Figure 25.			

* milligrams/square decimeter/day
** mils/year

Table 4. Comparative Corrosion Rates and Costs

Sample No.	Alloy	Estimated Cost finished sheet, $/lb **	Corrosion Rate, 35 mos. at 5300 ft., MDD	Corrosion Rate, 24 mos. at ocean surface, MDD
50	SS PH 15-7 MO, Cond. A	1.73	0.00	
52	SS 321	1.08	0.00	
55	Ti-4Al-3Mo-1V	13.00	0.00	
56	Ti-140A	unavailable	0.00	
57	Ti-6Al-4V	12.10	0.00	
58	Ni-Cr-Co-Mo 41	6.10	0.00	
70	Al 5052-H22	1.01	0.78	0.4*
62	Al Bronze	0.92	0.81	1.3
61	Lead	0.31	0.63	1.1
48	AlClad 7075-0	1.11	2.1	
59	Phosphor Bronze	1.14	2.2	3.1
51	SS-17-7 PH, Cond. A	1.44	0.0 to 3.6	
64	SS 304	0.86	0.0 to 3.2	1.5
53	Ni-Cr-Fe-Ti X-750	2.55	0.0 to 2.1	
54	Ni-Cr-Fe-Ti 600, Cond. A	1.90	0.0 to 3.1	
73	Ni-Cu 400, Annealed	1.89	3.2 to 5.8	2.9
74	Ni-Cu 400 (different heat)	1.89	5.1 to 8.1	
68	Al 3003-H24	0.99	3.5	1.4
71	Al 3003 (different heat)	0.99	3.5	
69	Al 1100-0	0.99	3.4	1.0
72	Al 2024-T3	1.11	3.6	0.8
132	Wrought Iron	unavailable	3.1	
66	Electrolytic Copper	1.08	3.1	3.4
67	Yellow Brass	0.98	3.7	
65	Commercial Brass	0.98	4.4	
49	Al 7178-0	1.33	5.3	
63	Bronze	0.80	5.2	
60	Naval Brass	1.08	5.8	5.9

* Metal panels, lost as result of rack failure, recovered after 30 months exposure.
** Prices quoted on 0.125 inch sheet in 100 lb. lots in most cases.

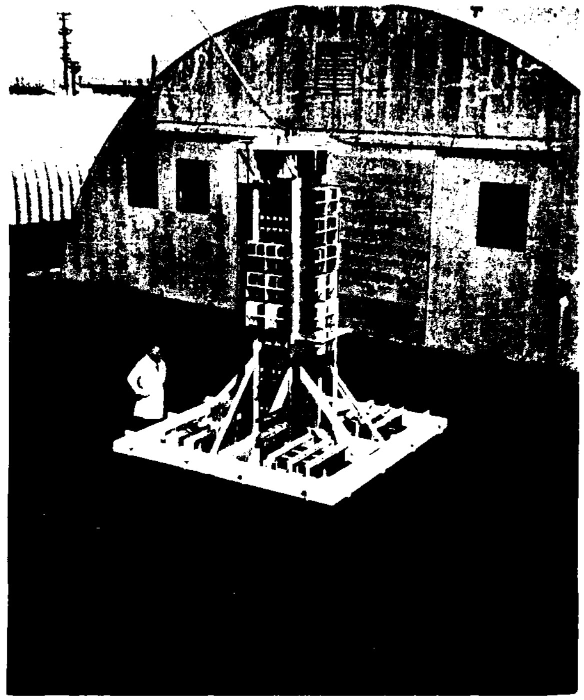


Figure 1. Submersible Test Unit.

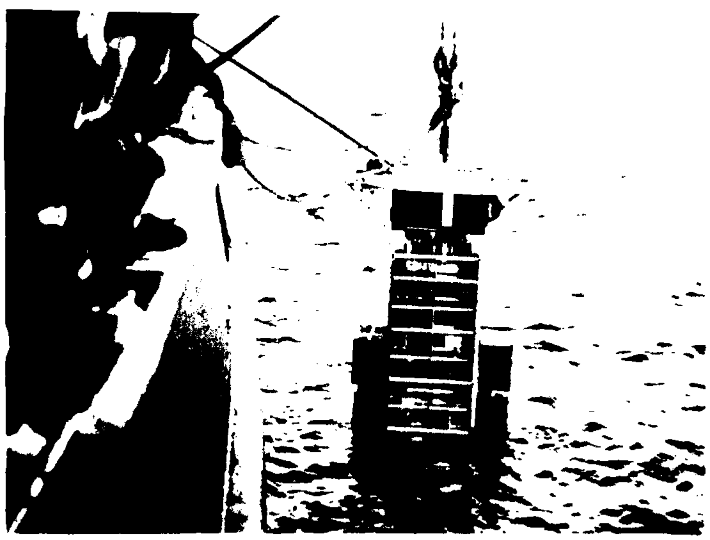
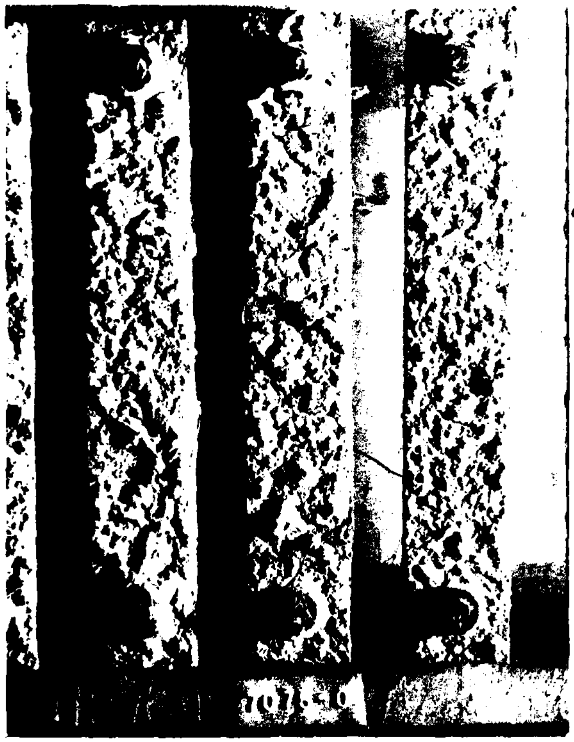


Figure 2. Retrieval of STU.



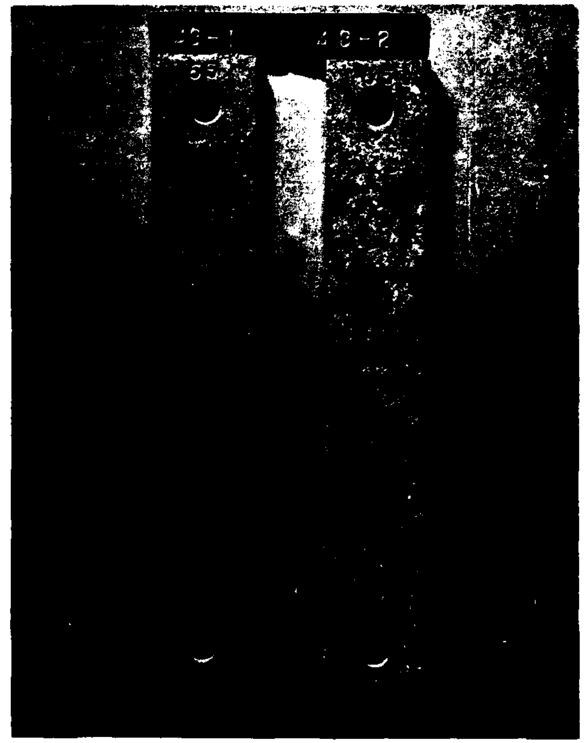


Figure 3. Sample 48, Aluminum Alclad 7075-0; QQ-A-287

(a) As recovered

(b) After cleaning

Figure 4. Sample 49, Aluminum 7178-0; MIL-A-9180

(a) As recovered

(b) After cleaning

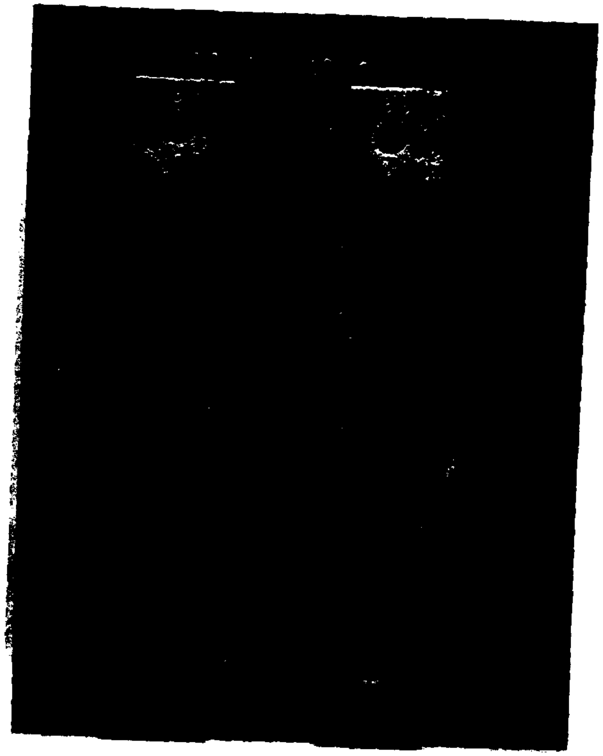


Figure 5. Samples 68 and 71, Aluminum 3003; QQ-A-359

(a) As recovered

(b) After cleaning

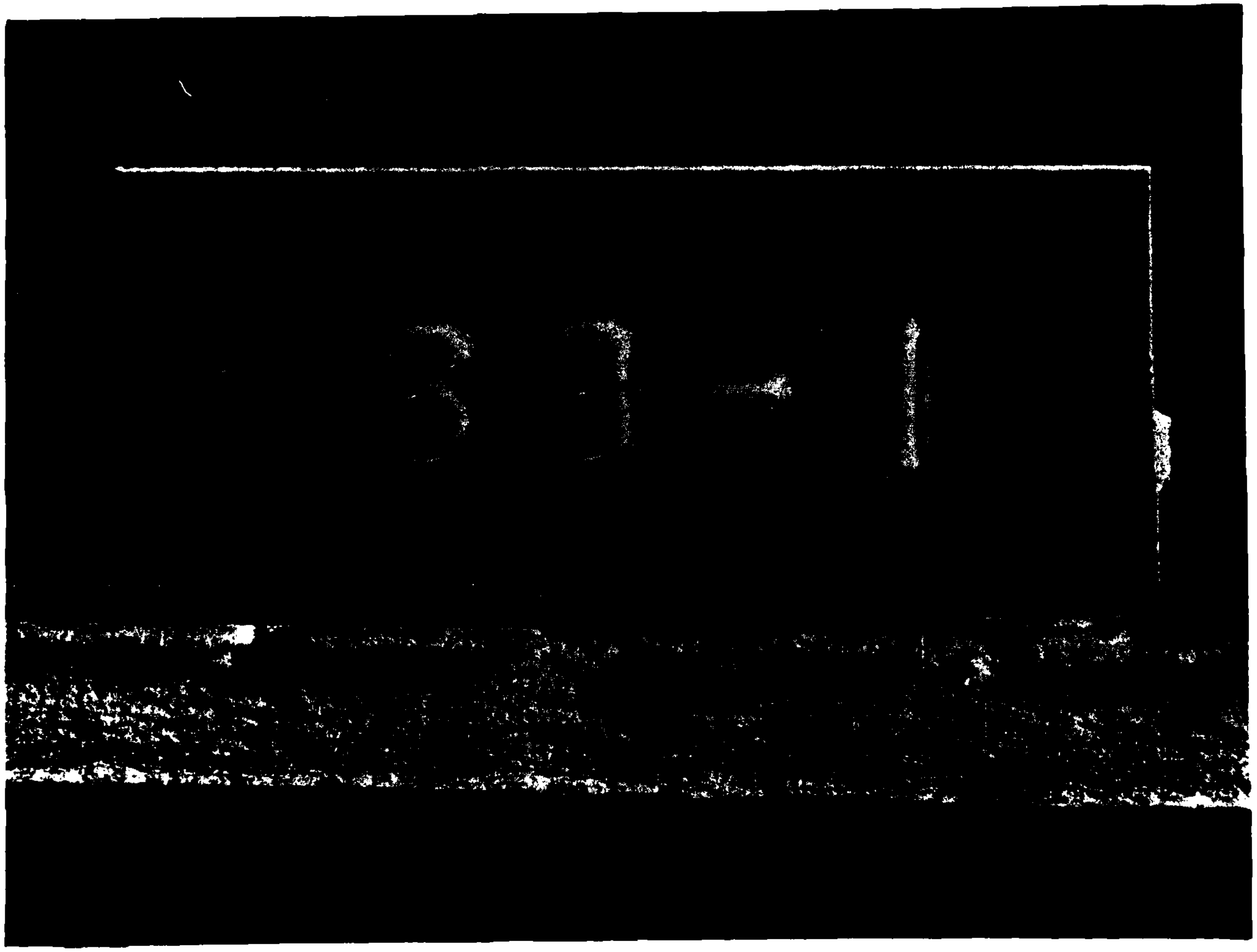


Figure 5. Samples 68 and 71, Aluminum 3003; QQ-A-359

(c) Detail of edge

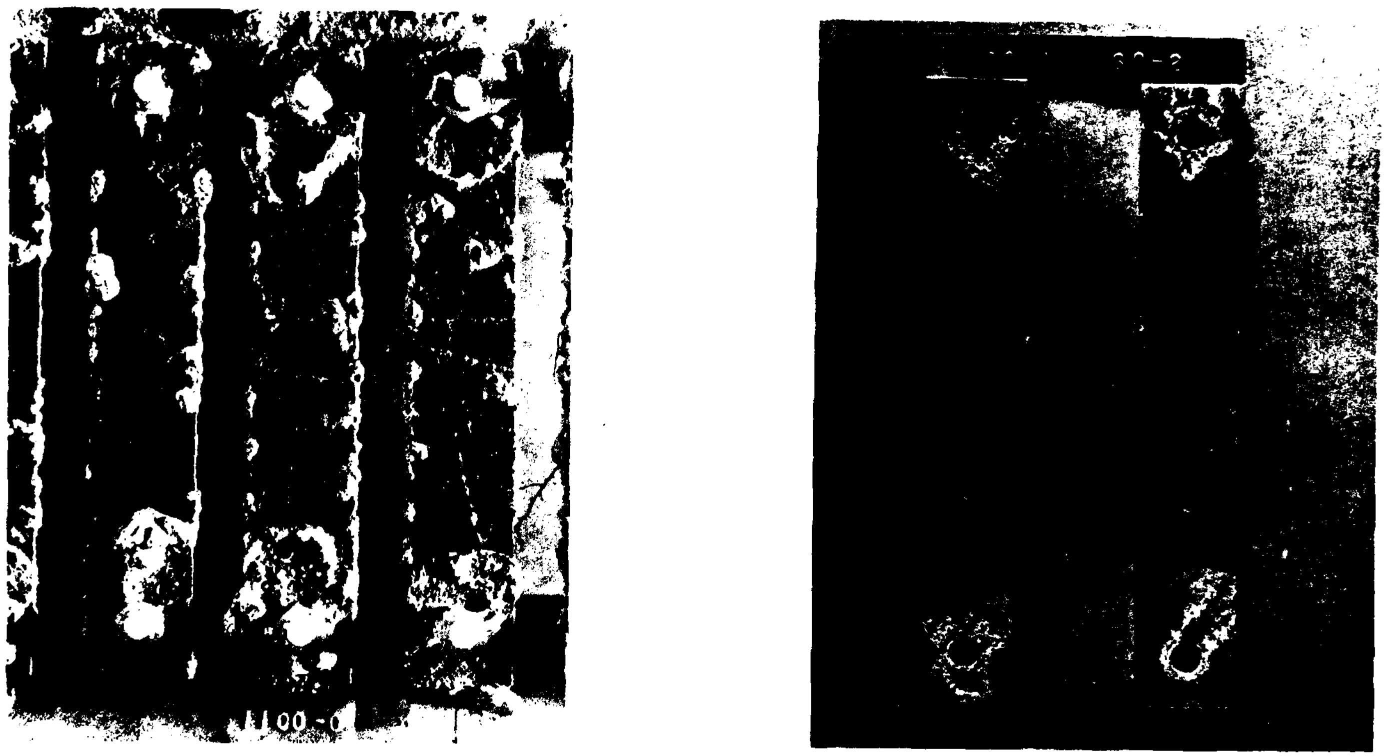


Figure 6. Sample 69, Aluminum 1100-0; QQ-A-561

(a) As recovered

(b) After cleaning

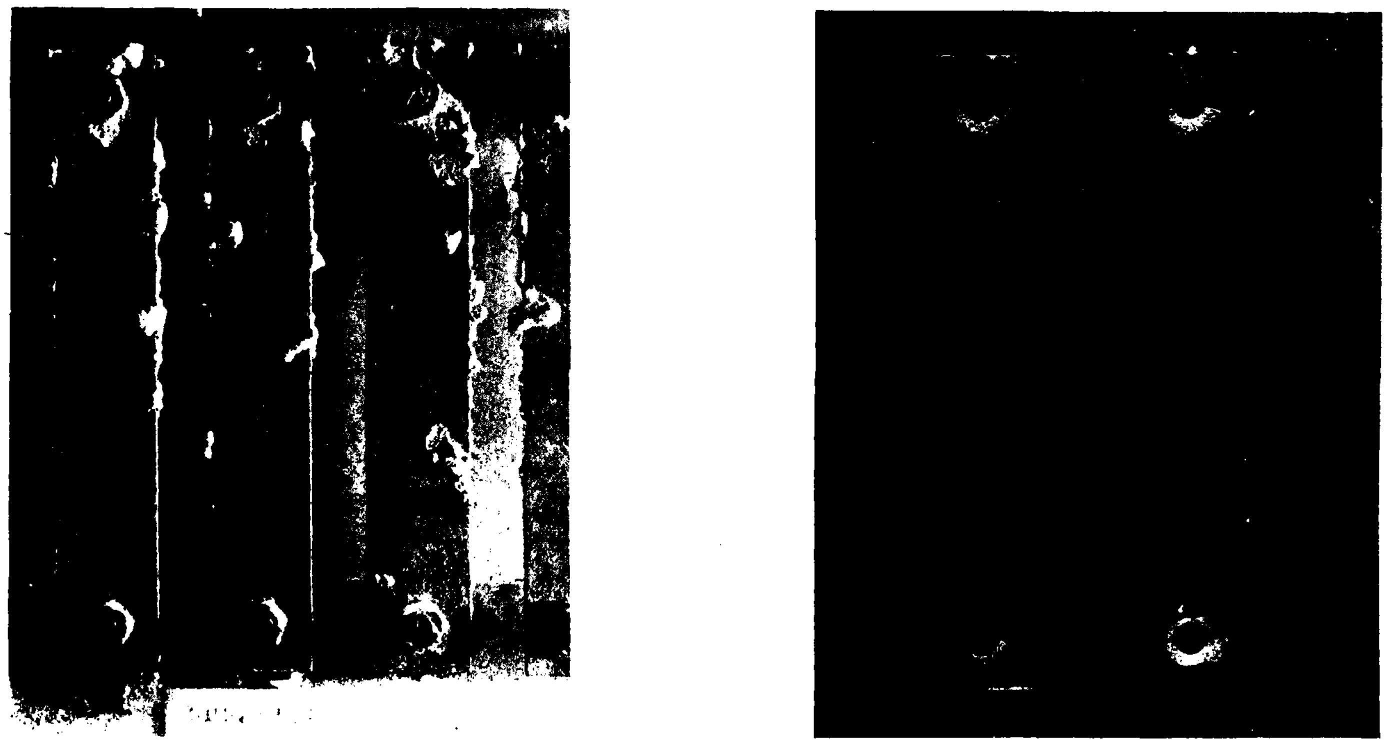


Figure 7. Sample 70, Aluminum 5052-H22; QQ-S-318

(a) As recovered

(b) After cleaning

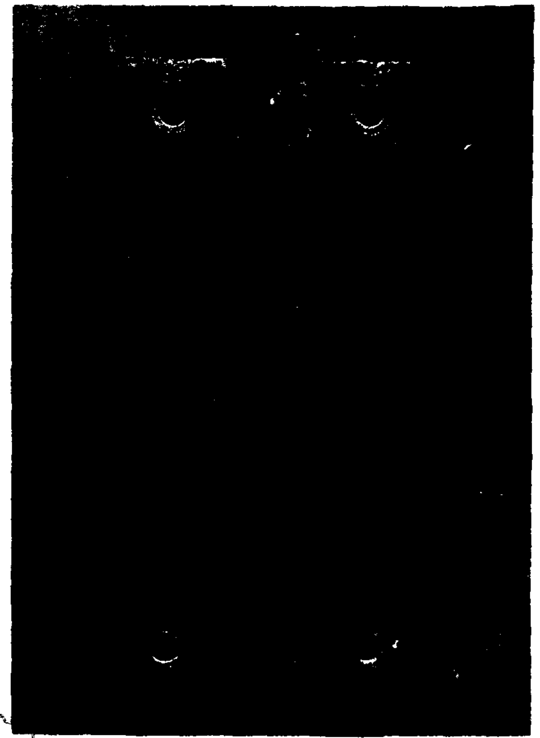


Figure 8. Sample 72, Aluminum 2024-T3; QQ-A-362

(a) As recovered

(b) After cleaning

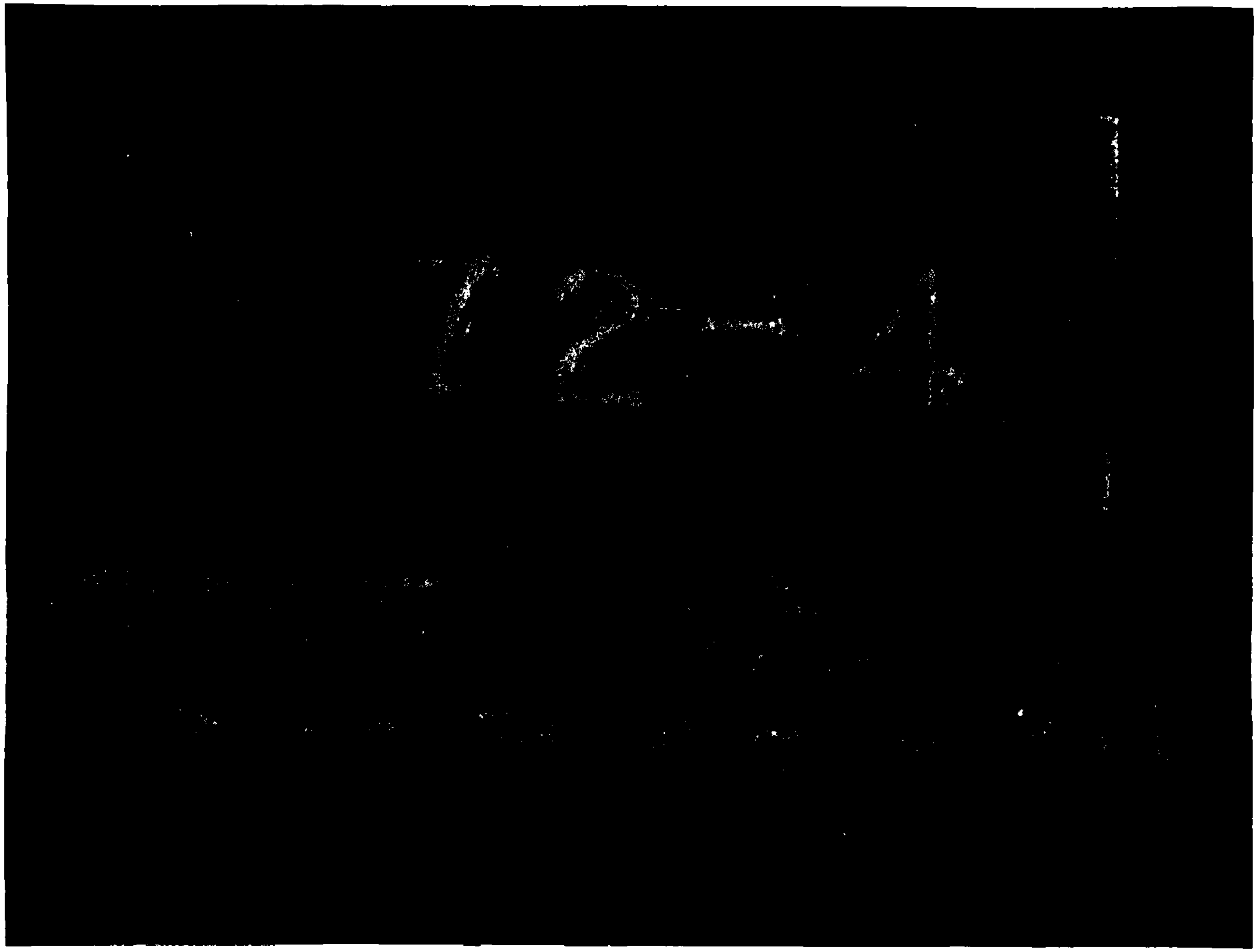


Figure 8. Sample 72, Aluminum 2024-T3; QQ-A-362

(c) Detail of edge

Figure 9. Sample 59, Phosphor Bronze, QQ-P-330, Comp. A

(a) As recovered

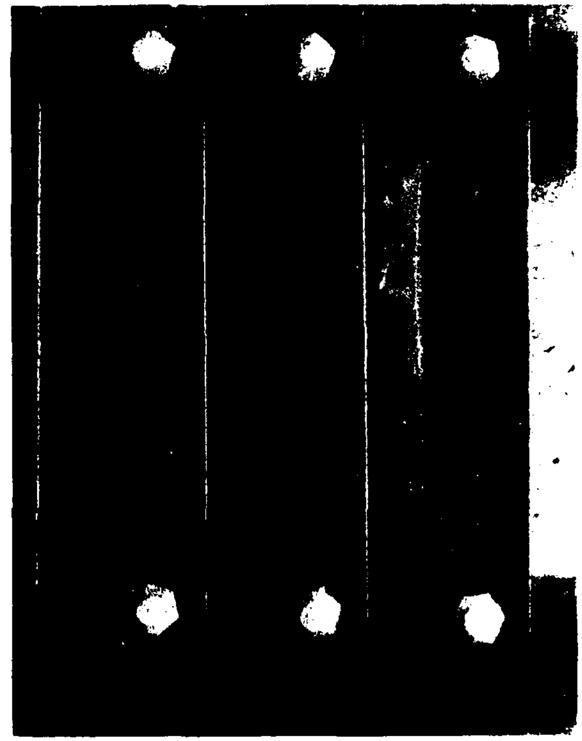


Figure 10. Sample 60, Naval Brass; MIL-N-994, Comp. A

(a) As recovered

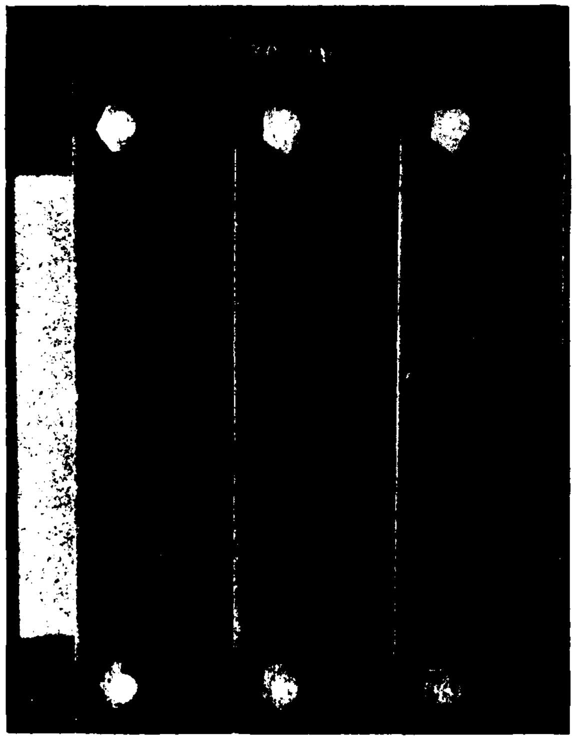


Figure 11. Sample 62, Aluminum Bronze; QQ-B-667, Comp. 3

(a) As recovered

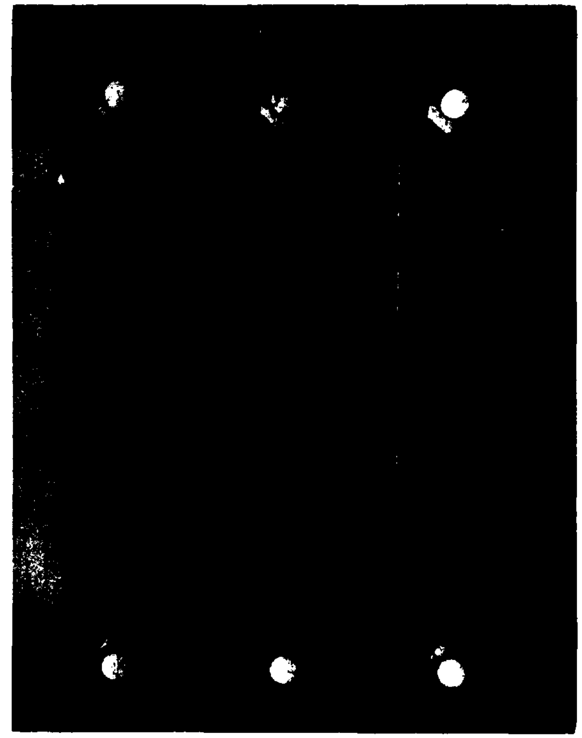


Figure 12. Sample 63, Bronze; QQ-M-80, Class A (Mn absent)

(a) As recovered

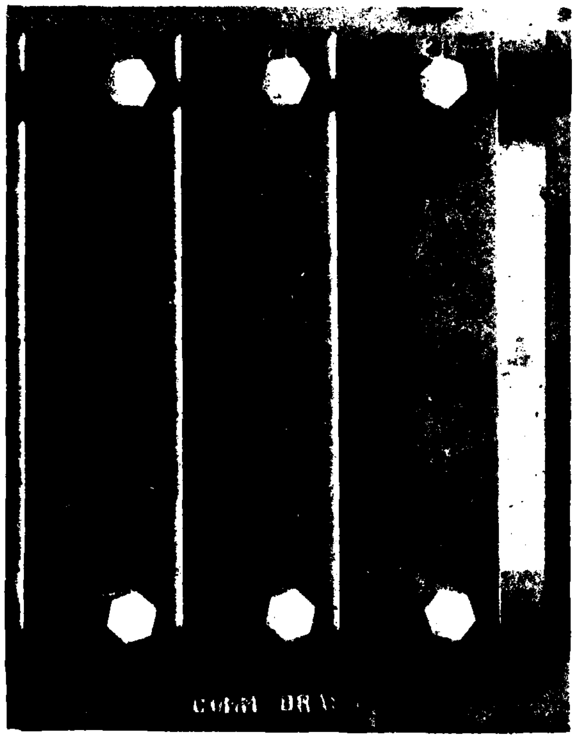


Figure 13. Sample 65, Commercial Brass; 63-68 Cu, Comp. A

(a) As recovered

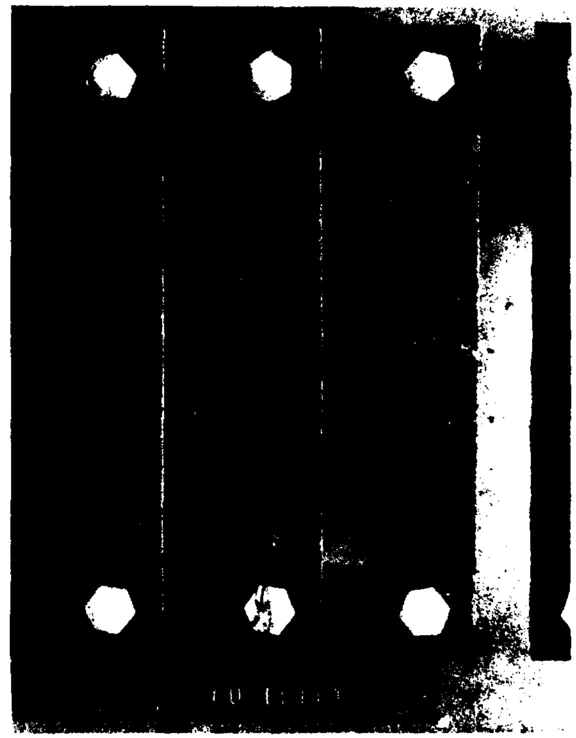


Figure 14. Sample 66, Copper, Electrolytic; QQ-C-576

(a) As recovered

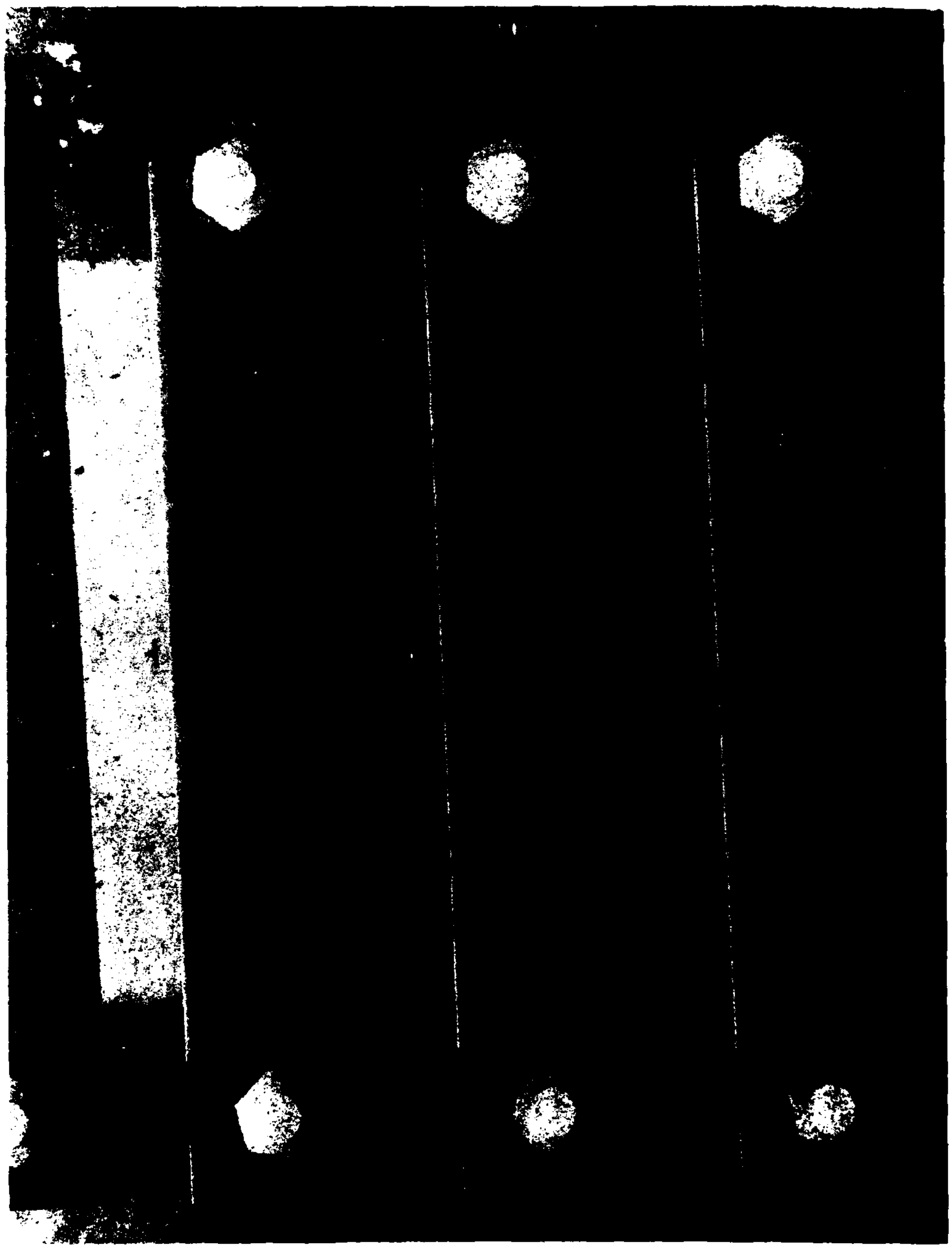
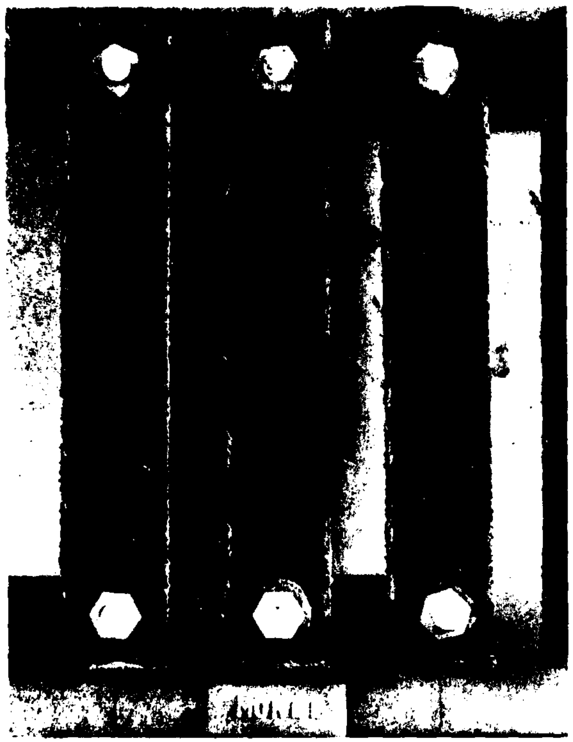


Figure 15. Sample 67, Yellow Brass; Revere Alloy 170

(a) As recovered



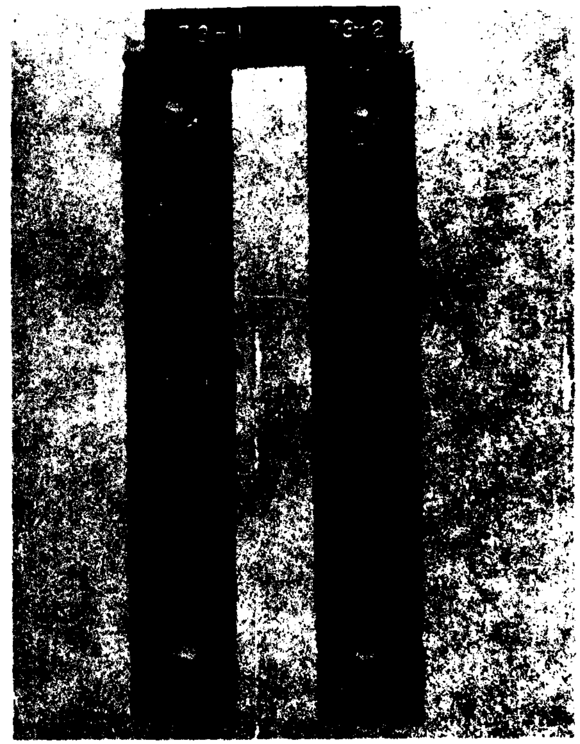


Figure 16. Sample 73, Ni-Cu 400, Annealed; QQ-N-281, Class A

(a) As recovered

(b) After cleaning

Figure 16. Sample 73, Ni-Cu 400, Annealed; QQ-N-281, Class A

(c) Detail of b

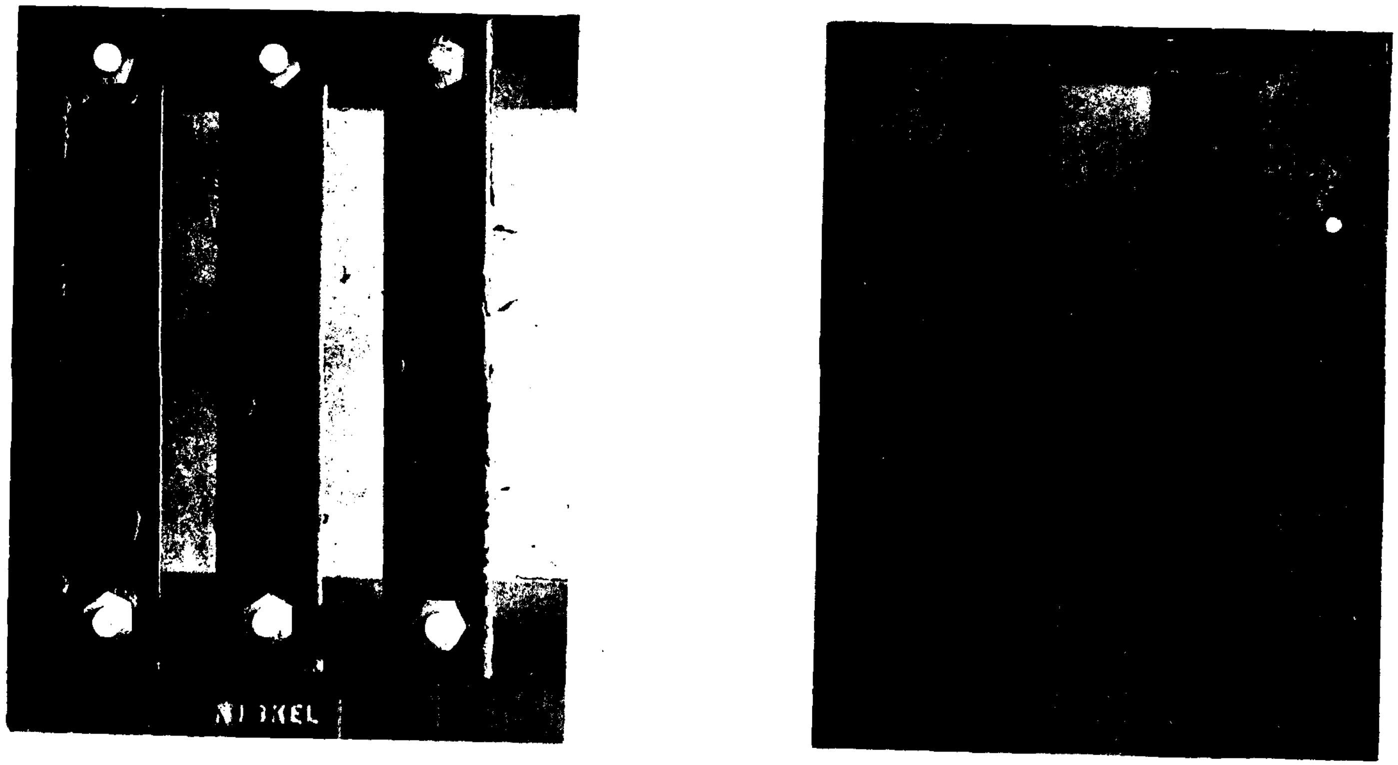


Figure 17. Sample 74, Ni-Cu 400
(a) As recovered
(b) After cleaning

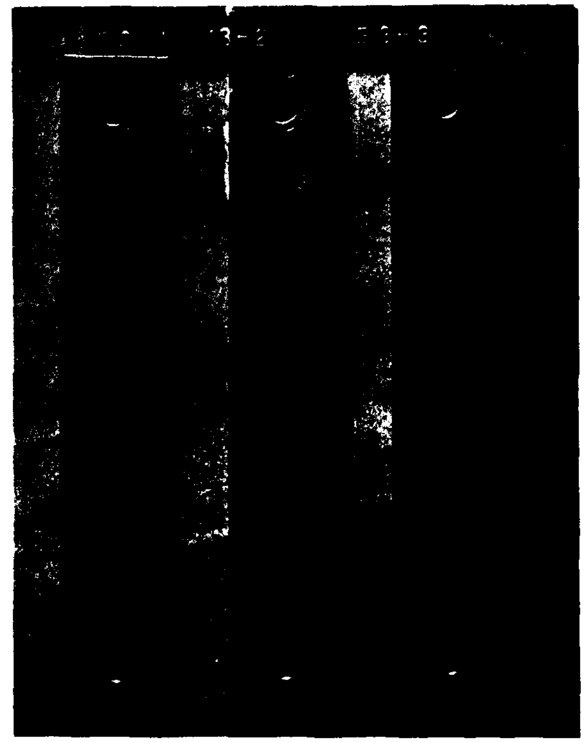


Figure 18. Sample 53, Ni-Cr-Fe-Ti X-750; AMS-5542-D

(a) As recovered

(b) After cleaning

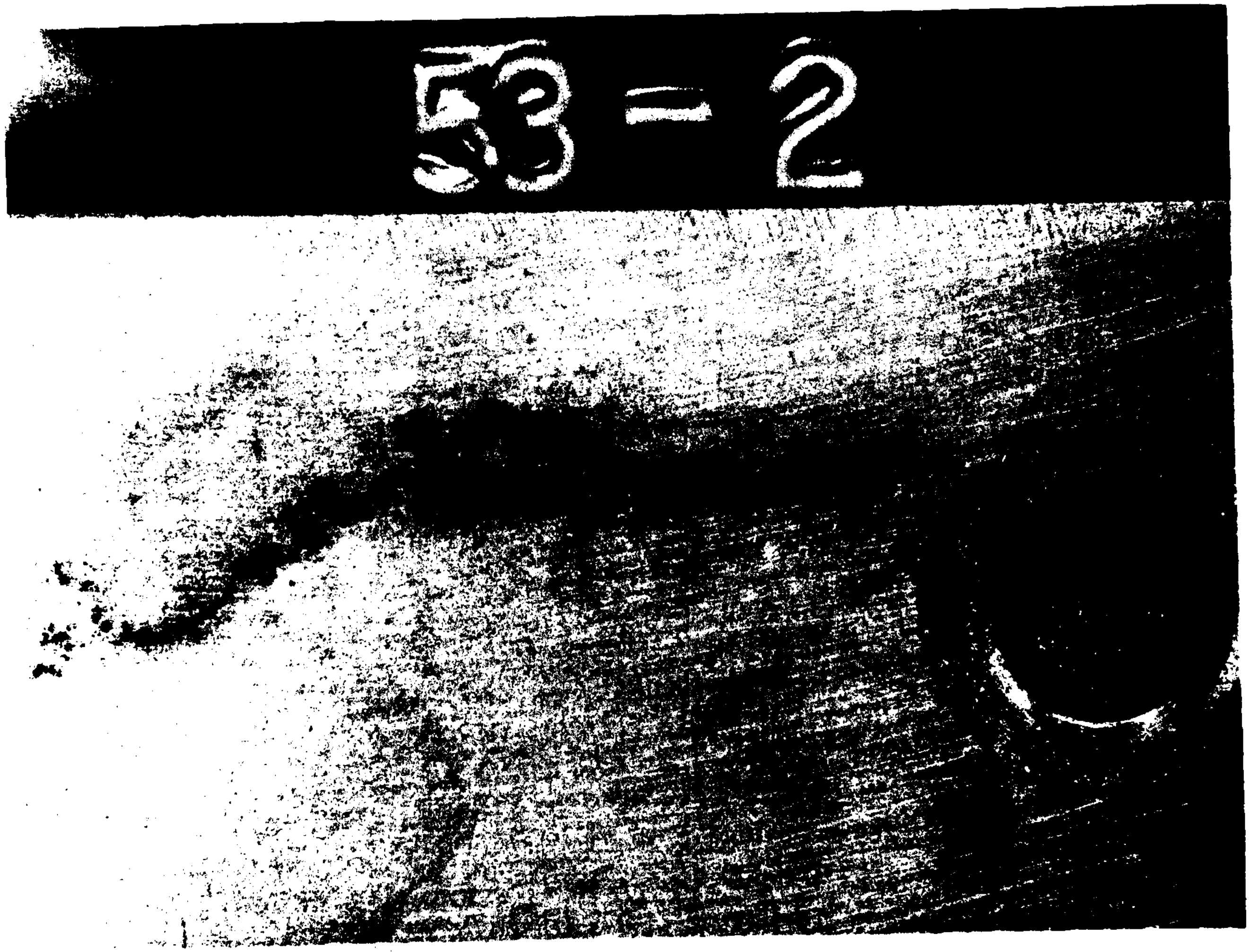
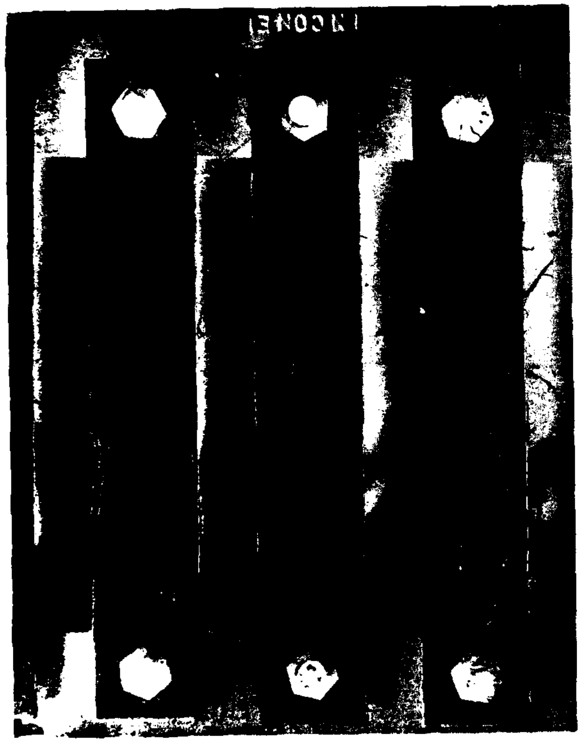
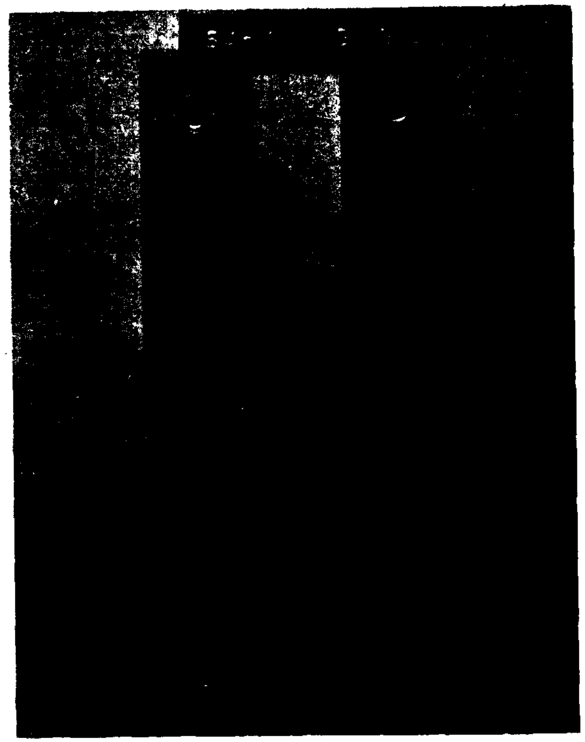


Figure 18. Sample 53, Ni-Cr-Fe-Ti X-750; AMS-5542-D

(c) Detail of b



(a) As recovered



(b) After cleaning

Figure 19. Sample 54, Ni-Cr-Fe-Ti 600, Cond. A; MIL-N-6840

Figure 19. Sample 54, Ni-Cr-Fe-Ti 600, Cond. A; MIL-N-6840

(c) Detail of b

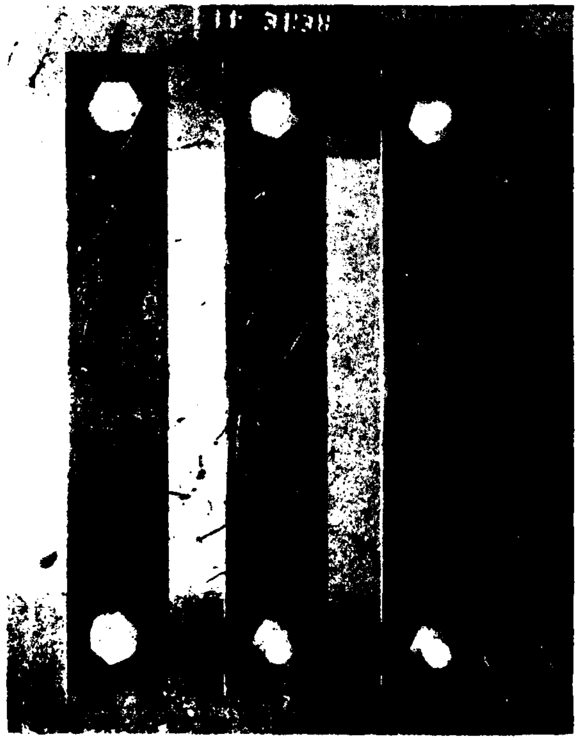
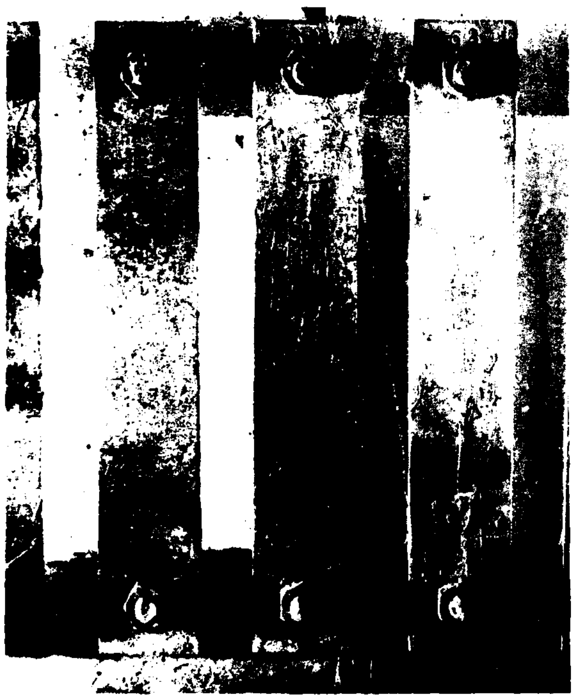


Figure 20. Sample 58, Ni-Cr-Co-Mo 41

(a) As recovered

Figure 21. Sample 50, Stainless Steel PH 15-7 MO, Cond. A; AISI, Type 632

(a) As recovered



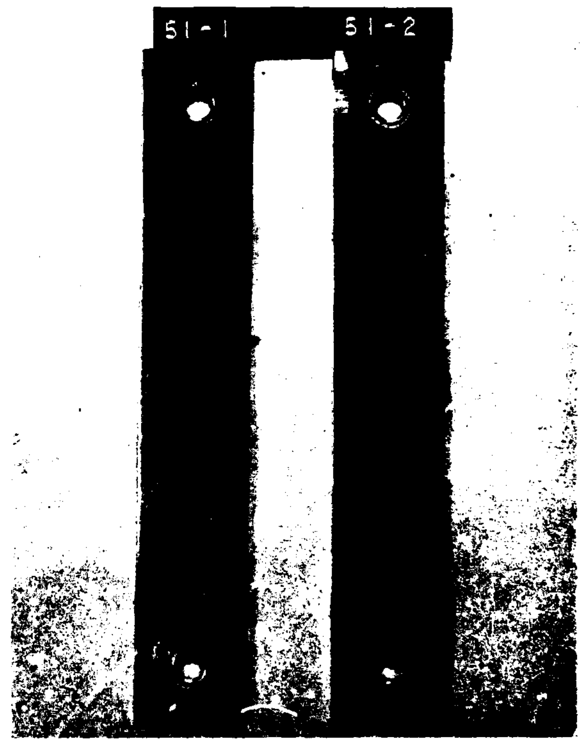


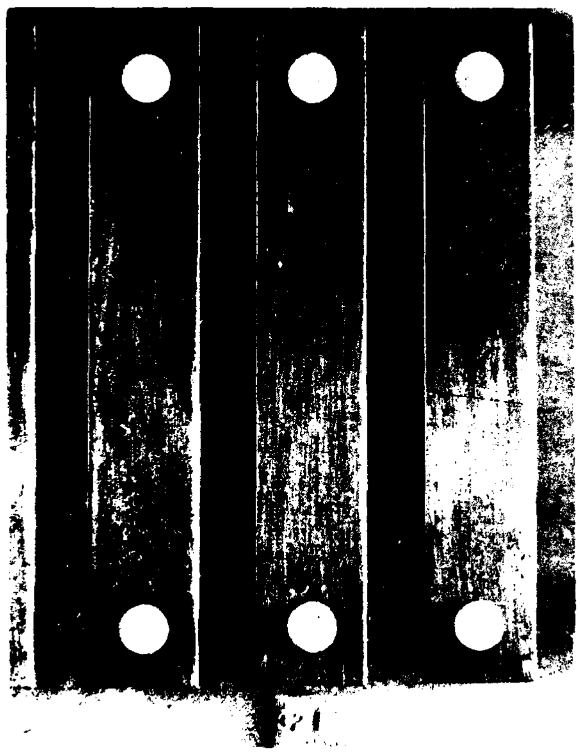
Figure 22. Sample 51, Stainless Steel 17-7 PH, Cond. A; MIL-S-25043B

(a) As recovered

(b) After cleaning

Figure 22. Sample 51, Stainless Steel 17-7 PH, Cond. A; MIL-S-25043B

(c) Detail of b



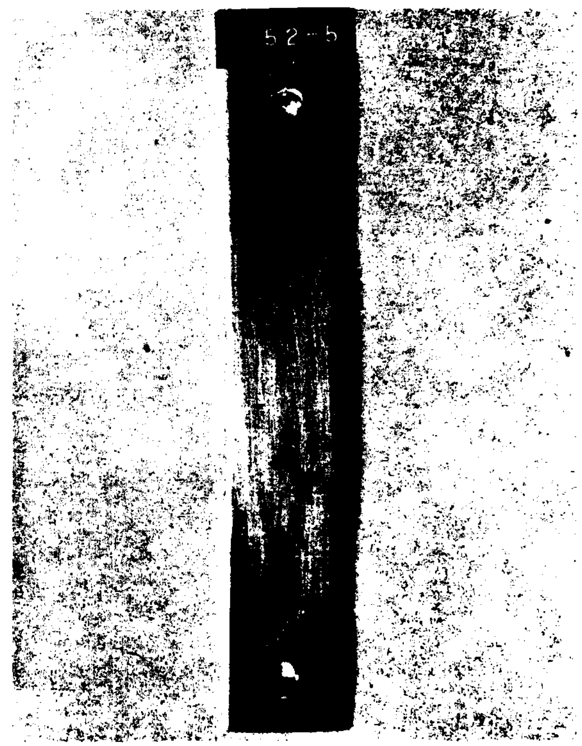


Figure 23. Sample 52, Stainless Steel 321; MIL-S-6721A

(a) As recovered

(b) After cleaning

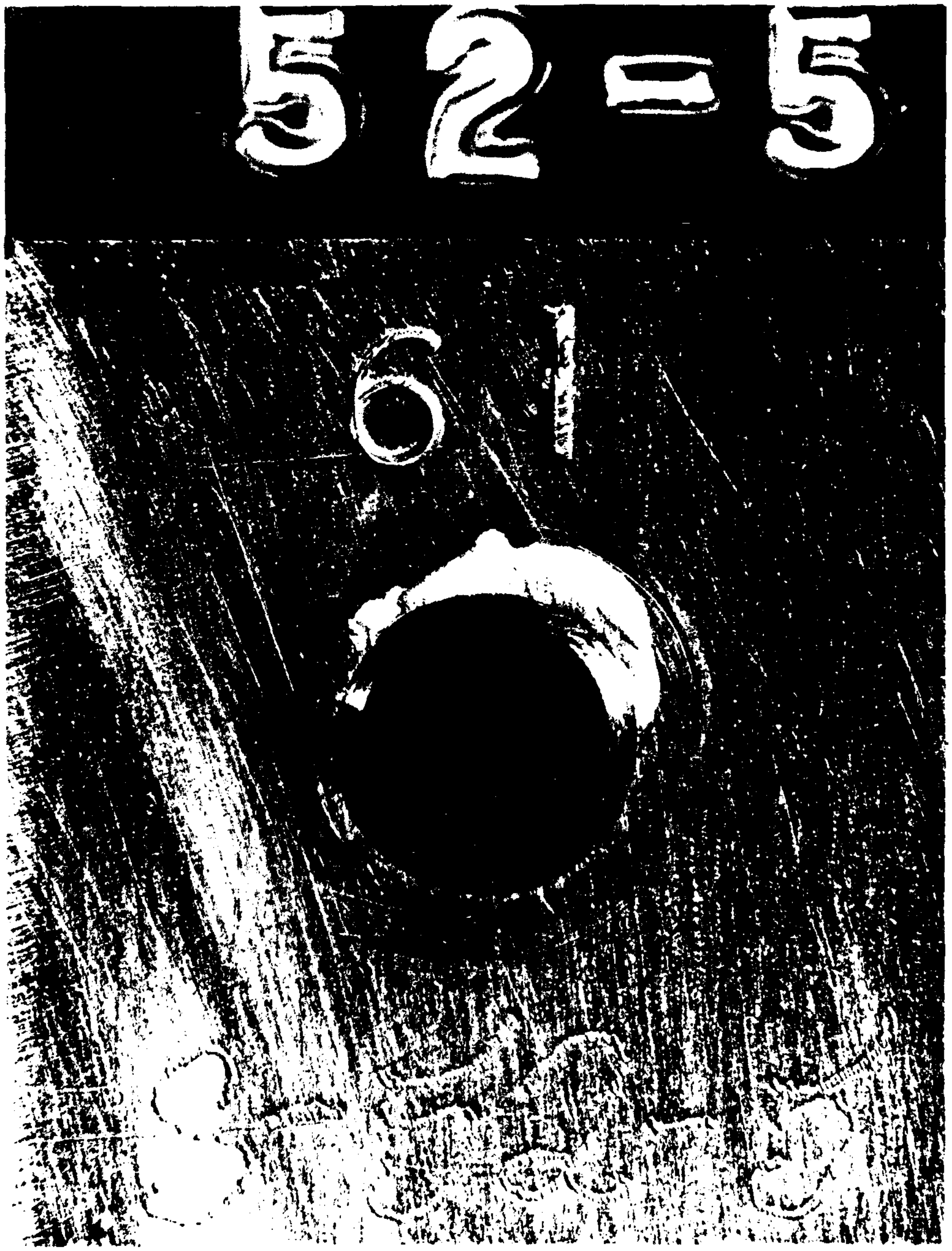
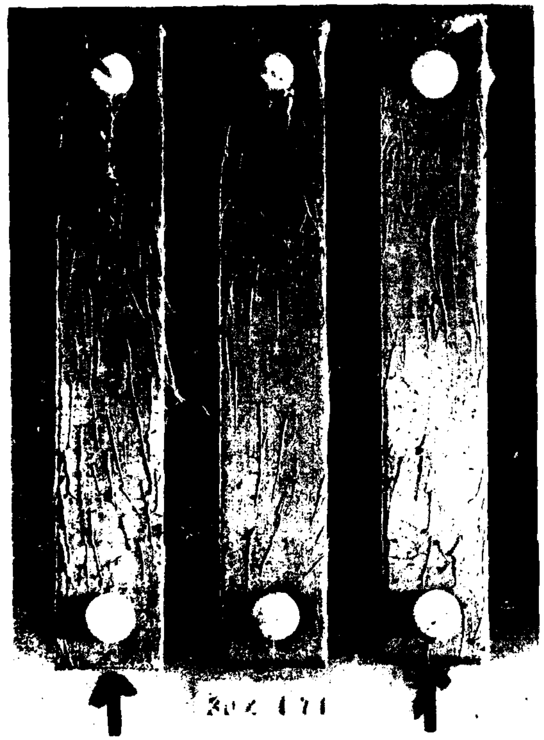


Figure 23. Sample 52, Stainless Steel 321;
MIL-S-6721A

(c) Detail of b



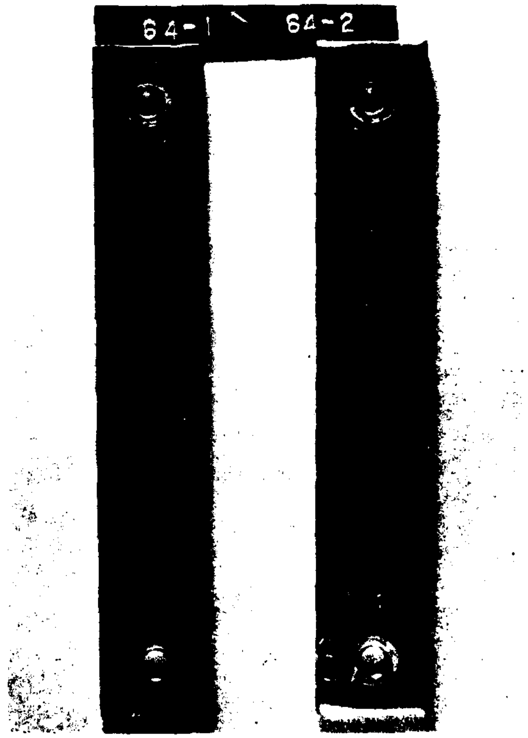


Figure 24. Sample 64, Stainless Steel 304; MIL-S-854, Class 1

(a) As recovered

(b) After cleaning

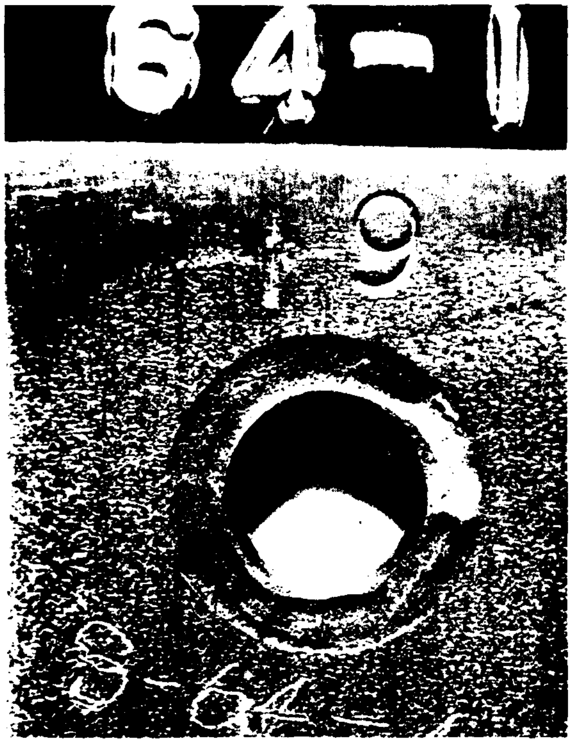


Figure 24. Sample 64, Stainless Steel 304; MIL-S-854, Class 1
(c) Detail of b

Figure 25. Sample 132, Wrought Iron

Figure 26. Sample 55, Ti-4Al-3Mo-1V; AMS 4912

(a) As recovered

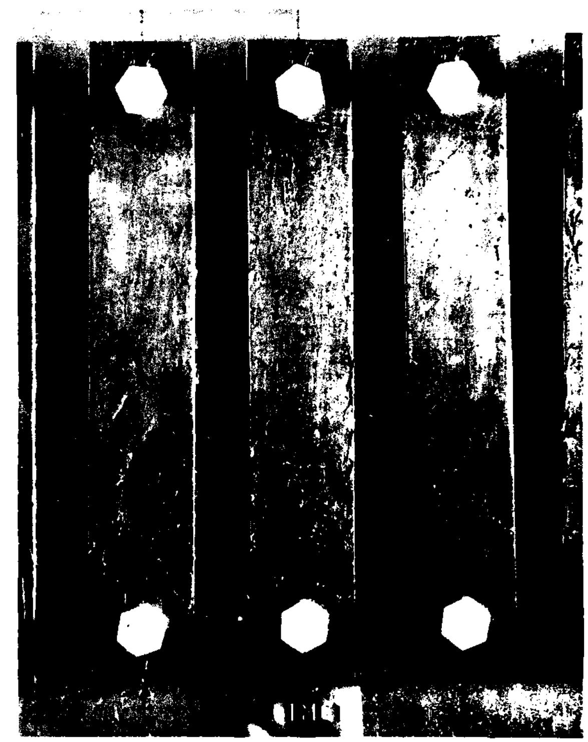


Figure 27. Sample 56, Ti-140A (not a standard alloy); NA2-7125J, Class B

(a) As recovered

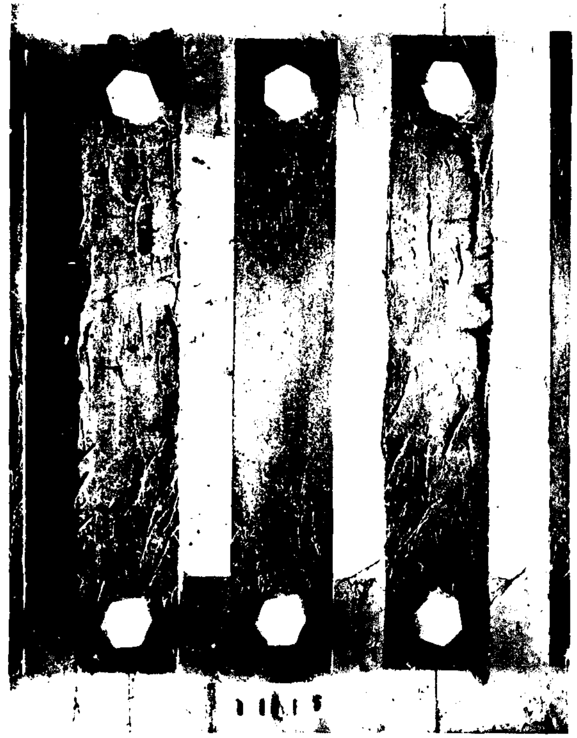


Figure 28. Sample 57, Ti-6Al-4V; AMS-4928A

(a) As recovered

Figure 29. Sample 61, Lead; QQ-L-201, Grade B

(a) As recovered

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
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13. ABSTRACT

Corrosion rate data are given for several sets of metals and alloys exposed to the deep ocean environment off the coast of sourthern California at a depth of 5300 feet for 1064 days. The sets include some aluminum alloys; stainless steels; brasses and bronzes; titanium alloys; alloys containing nickel, chromium and other metals; a nickel-copper alloy; as well as sets of copper, lead and wrought iron. All specimens of six of these sets did not corrode at all. In some of the other sets there was relatively uniform corrosion up to rates of about 6 $mg/dm^2/day$, but in others the individual specimens varied considerably in their corrosion rates.

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Metals						
Alloys						
Corrosion						
Ocean Environments						
Aluminum Alloys						
Stainless Steels						
Brasses						
Titanium Alloys						
Nickel Alloys						